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SHRINKAGE-COMPENSATING CEMENT FOR AIRPORT PAVEMENT

Phase 3 - Fibrous Concretes

John R. Keeton

September 1980

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16. Abstract

Details of a research study on shrinkage-compensating fibrous concrete for airport pavements are presented. A total of 77 slab-type prisms 1 ft^2 and 4, 6, and 8 in. thick were subjected to shrinkage in 50% RH. Concrete mixes containing 5.5, 6.5, and 7.5 bags of shrinkage-compensating cement were used in the study. Fly ash was also used for better workability and later added strength. Fiber contents used were 1.0, 1.5, and 2.0% by volume of the concrete. Residual concrete compressive stresses are used as a basis for recommendation of transverse joint spacing of 150 ft for expansive fibrous concrete overlays.

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INTRODUCTION

Sometimes it is necessary to increase the strength of existing airport pavements by applying a concrete overlay. Thickness of the overlay in a given case depends upon the required extra strength as well as the thickness and condition of the existing pavement. Recently, fibrous concretes have been used in overlays at the McCarran International Airport, Las Vegas and Cannon International Airport, Reno, both in Nevada. The Federal Aviation Administration (FAA) sponsored research on design of fibrous concretes which was concluded in 1974 (Ref 1). Reference 1 also includes a detailed bibliography of work done to 1974 on fibrous concretes.

Research conducted at the Navy's Civil Engineering Laboratory (CEL) on airport pavements made with expansive cements and reinforced with welded wire fabric was recently completed (Ref 2). At the request of FAA, the original research at CEL was extended to include investigation of expansive cement in fibrous concretes, with the objective of determining whether transverse joint spacing can be lengthened by using expansive fibrous concretes as overlays. This report is an addendum to Reference 2.

EXPERIMENTAL PROGRAM - PHASE THREE

The experimental program utilized to furnish research data to accomplish the objective is summarized in Table 1 and outlined below.

Aggregates

The aggregate used in this study was 3/8-in. maximum size river gravel and river sand, commonly used for concrete in the area. The aggregate is good quality and meets ASTM C33-78 requirements.

Cements

The shrinkage-compensating cement used in this study was ChemComp® (ACI Designated Type K). Mortar bar expansions (Ref 3) averaged 550 microstrain (0.055%) at 7 d. Fly ash (ASTM C618-78) was used to improve

1. Federal Aviation Administration. Report No. FAA-RD-74-31: Steel Fibrous Concrete for Airport Pavement Applications, by F. Parker, Jr., Nov 1974.
2. Federal Aviation Administration. Report No. FAA-RD-79-11: Shrinkage-Compensating Cement for Airport Pavement, Phase 2, by John R. Keeton, Sep 1979. (Civil Engineering Laboratory Technical Note N-1561)
3. American Society for Testing and Materials. ASTM C806-75: Standard Test Method for Restrained Expansion of Expansive Cement Mortar, Annual Book of ASTM Standards, Part 13, 1979, pp 444-447.

workability and to increase later strength; it was not used as a cement substitute. Type II Portland cement was used in comparable mixes for strength comparisons only.

Fibers

Fibers were made of carbon steel and measured 0.010 in. by 0.022 in. in cross section and 1 in. long. Fiber content is stated on a volume basis, e.g., 1.5% volume means $0.015 \times 27\ ft^3 = 0.40\ ft^3/yd^3$.

Concrete Mixes

Concrete mixes used in Phase 3 are listed in Table 2. In terms of shrinkage-compensating cement alone, the cement contents are 517 lb (5.5 bags), 611 lb (6.5 bags), and 705 lb (7.5 bags) per cubic yard for 7.9 ECF, 9.3 ECF, and 10.7 ECF mixes, respectively. Mix designation 7.9 ECF contained 5.5 bags of shrinkage-compensating cement and 2.4 bags (7.9 minus 5.5) of fly ash per cu yd of expansive concrete with fibers. Slumps ranged from 3 in. to 4 in. and air contents form 5% to 7% (ASTM C231-78). Relative amounts of ingredients in the mixes were selected to approximate the mixes used in the overlays at Las Vegas and Reno. The mixes also are based on recommendations of the American Concrete Institute (Ref 4).

Slab-Type Prismatic Specimens

To provide basic expansion-shrinkage data, slab type prismatic specimens 12 x 12 in. in plan with the following thicknesses to simulate typical fibrous concrete overlays were fabricated:

a. 4 in. thick
b. 6 in. thick
c. 8 in. thick

Embedded Strain Gages

Gages for measuring concrete strain were an embeddable type consisting of a single wire about 5 in. long, cast in plastic. In the 6- and 8-in. thick prisms, embedded strain gages were placed at 1 in. from the top and at middepth; in the 4-in. thick prisms, gages were placed at 1 in. from the top and 1 in. from the bottom.

Strain Measurement

Concrete strain measurement with embeddable electrical resistance strain gages was begun as soon as practicable after casting of the concrete. Strain gage readings were made with a portable strain indicator. Strain is reported in microstrain (μin./in.).

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4. American Concrete Institute. Manual of Concrete Practice, Part 3, 544-8, Table 3-2, 1978.

Strength Specimens

Cylinders and beams were made with expansive concretes as well as Type II Portland cement concretes to establish compressive and flexural strengths as well as Young's moduli. All specimens were cured for 28 d, 3 mo, or 6 mo in fog and then tested in accordance with ASTM C39-72 for compressive strength and ASTM C78-75 for flexural strength.

Curing

Following final set, the slab-type specimens were cured under wet burlap for 24 hr. Then the sides and bottom were sealed with a butyl rubber coating and a piece of wet burlap placed over the top surface. Sealing was done to prevent escape of moisture during curing and drying from the sides and bottom. This simulates a full-size concrete overlay exposed to the elements only at the top. The wet burlap was then covered with aluminum foil for a total curing period of 28 d. At 28 d, the prisms were placed in a drying (shrinkage) environment.

Shrinkage Environment

Following the 28-d curing period during which concrete expansion was obtained, the prisms were exposed to drying shrinkage in 50% relative humidity (RH) at 73°F for a total of 365 d.

TEST RESULTS

Concrete Strengths

Flexural and compressive strengths and Young's moduli for the concretes used in this study are shown in Table 3. Six-month flexural strengths of expansive concretes (ECF) averaged 1,160, 1,300, and 1,240 psi for fiber volumes of 1.0%, 1.5%, and 2.0%, respectively. Corresponding flexural strengths of portland cement concretes (PCC) are 1,200, 1,290, and 1,330 psi. The two sets of values are very close. Corresponding values of compressive strength and Young's modulus for the ECF and PCC are comparable.

Concrete Expansion

Concrete expansions of 4-, 6-, and 8-in. thick prisms after 28 d of curing are shown in Table 4 (a), (b), and (c), respectively. As expected, the higher the fiber content, the lower the expansion. For the concrete to remain in compression during its useful life, the expansion must be larger than the subsequent shrinkage. Since the actual steel percentage of the different fiber contents (1.0%, 1.5%, and 2.0%) is unknown, calculation of the concrete compressive stress due to expansion must be based on equivalent steel percentage determined by comparison with other data (see Discussion Section of this report).

Concrete Shrinkage and Net Concrete Strains

Concrete shrinkage for all mixes and all prism thicknesses in 50% RH are shown in Tables 5, 6, and 7 for depths below the top surface of 1, 3, and 4 in., respectively. Generally, shrinkage with 1.0% fibers was slightly higher than with 1.5% and 2.0% fibers. Shrinkages of the three mixes showed no consistent relationship, i.e., no one mix had consistently higher or lower shrinkage than the others at all depths from the top.

Tables 8, 9, and 10 show residual expansions after 1 yr of shrinkage at 50% RH for all prism thicknesses at 1, 3, and 4 in. from the top, respectively. Shrinkages are shown as negative to emphasize that shrinkage strain is in a direction opposite to expansion. Positive residual strains mean that the shrinkage did not exceed the expansion, leaving the concrete in compression after all shrinkage had occurred. When the residual strain is negative, the shrinkage exceeded the expansion, leaving the concrete in tension after the shrinkage. The object of using shrinkage-compensating cement is to provide enough expansion to induce sufficient compression in the concrete to counterbalance subsequent shrinkage. Only when the residual is positive (concrete still in compression) can the concrete be expected to be crack-free after shrinkage. No consideration is made here for stresses and strains caused by external loads.

As stated in the Phase 2 report, shrinkage strains in 20% RH average about 30% more than those in 50% RH; i.e., shrinkage in 20% RH = shrinkage in 50% RH x 1.3. Accordingly, Table 11 lists calculated 1-yr shrinkages at 20% RH for all prism sizes and mixes at depths of 1, 3, and 4 in. Tables 12, 13, and 14 show residual expansions after 1 yr of shrinkage at 20% RH for all prisms thicknesses at 1, 3, and 4 in. from the top, respectively. As before, only where the residual is positive can the concrete be expected to be crack-free after shrinkage. Although 20% RH is a rather severe ambience, these data are included to indicate behavior under severe shrinkage conditions and to make the analysis more complete.

Table 15 shows the thickness-mix-steel volume combinations that provided residual strains which were compressive (positive) after 1 yr of shrinkage in 50% RH. Table 16 shows the combinations that provided residual strains after 1 yr of shrinkage in 20% RH. In general, Table 15 shows that residual strain increases with increase in thickness and cement content but decreases as the fiber volume increases. A similar trend is indicated by Table 16. A comparison of the combinations in Tables 15 and 16 indicates that the 20% RH shrinkage environment was more severe than 50% RH in retaining compressive strains.

DISCUSSION

Although actual steel percentages resulting from 1.0, 1.5, and 2.0% fiber volumes are unknown, reference can be made to previous work in reinforced expansive concretes (Ref 5). Figure 5 of Reference 5 shows

5. Civil Engineering Laboratory. Technical Note N-1504: Expansive Cement Concretes for Naval Construction, by John R. Keeton, Port Hueneme, Calif., Nov 1977.

expansion versus steel percentage for 1-in. thick prisms of concrete made with 7.5 bags per cu yd of shrinkage-compensating cement, which corresponds, in terms of expansive cement content, to the 10.7 ECF mix used in this study. Figure 1 of this report contains the pertinent data from Figure 5 of Reference 5. Expansion values taken from Table 4 of this report for the 10.7 ECF mix can be used to estimate an equivalent steel percentage for the fibers. Table 17 shows a compilation of these estimates for all prisms. For example, from Table 4A, the average expansion between 1- and 3-in. from the top at 1.0% fibers (10.7 ECF mix) is 596 microstrain [650 + 543 ÷ 2]. Entering Figure 1 at an expansion value of 596 (ordinate), the equivalent steel percentage is found to be 0.33%. In a similar manner, the expansions in Table 4 are averaged for all depths shown and equivalent steel percentages taken from Figure 1. For 6-in. thick prisms at 1.0% fibers (Table 4B), the average expansion is 590 microstrain [690 + 580 + 500 ÷ 3]. In Figure 1 the equivalent steel percentage for 590 microstrain is about 0.33%. The remainder of Table 17 is obtained in the same manner.

Having equivalent steel percentages enables calculation of residual concrete compressive stresses (f_c) by the formula $f_c = \varepsilon \times p \times E_s$, where ε = residual concrete strain, p = steel percentage, and E_s = Young's modulus for the steel which is 28×10^6 psi (Ref 2). Utilizing the residual strains in Table 15 and averaging the values at the two depths shown for each prism, the residual concrete compressive stresses for the 10.7 ECF mix are shown in Tables 18 and 19 after 1 yr at 50% RH and 20% RH, respectively. For example, in Table 15A for 10.7 ECF, the average residual compressive strain of the 4-in. thick prisms at 1.0% fibers is 156 microstrain [195 + 118 ÷ 2]. Having the residual strain (156) and the corresponding steel percentage for the 4-in. thick prism from Table 17 (0.33%), the concrete compressive stress can be calculated: $f_c = 156 \times 10^{-6} \times 0.0033 \times 28 \times 10^6 = 14$ psi, shown in the 4-in. thick column at 1.0% fibers in Table 18.

Residual concrete compressive stresses after 1 yr at 50% RH shown in Table 18 for 6- and 8-in. thick prisms compare favorably with residual stresses shown in Table 8 of Reference 2 for expansive concretes reinforced with welded wire fabric. Of the residual compressive stresses shown in Table 19 after 1 yr at 20% RH, only the stress for the 8-in. thick prism at 1.0% fibers is comparable to those in Table 10 of Reference 2.

Since the equivalent steel stresses were estimated from data obtained on different specimens and with different aggregates, it is expedient to be conservative in recommending transverse joint spacing for fibrous expansive concrete overlays. For an average ambience of 50% RH and using a 6- or 8-in. thick overlay at 1.0% fibers, it seems reasonable to suggest a transverse joint spacing of 150 ft until a full-size experimental overlay can be constructed. For an average ambience of 20% RH and using an 8-in. thick overlay at 1.0% fibers, a transverse joint spacing of 150 ft seems justified.

CONCLUSIONS

1. For an ambience averaging 50% RH, a transverse joint spacing of 150 ft is appropriate only for 6-in. thick overlays at 1.0% fibers and for 8-in. thick overlays at 1.0% or 1.5% fibers.

2. For an ambience averaging 20% RH, a transverse joint spacing of 150 ft is appropriate only for 8-in. thick overlays at 1.0% fibers.

3. Physical properties of expansive fibrous concrete at 28 d, 3 mo, and 6 mo have approximately the same values as ordinary Portland cement fibrous concrete. Consequently, the overlay thicknesses using expansive fibrous concrete can be the same as those using ordinary Portland cement fibrous concrete.

RECOMMENDATIONS

1. To provide a full-size demonstration, it is recommended that at the earliest opportunity one lane of a moderate length of 6- or 8-in. thick overlay be designated as a research project. This section should be made with a shrinkage-compensating cement and fly ash mix of 10.7 bags per cu yd and should contain 1.0% fibers by volume. The shrinkage-compensating cement used should be ACI Type K which provides 7-d mortar bar expansions in the range of 500 to 900 microstrain (0.050 to 0.090%). The minimum expansion should be 500 microstrain (0.050%). The experimental lane should be instrumented with embeddable strain gages to determine expansion and subsequent shrinkage. It is recommended that the transverse joint spacings be as follows: the first 10 joints at 150 ft, the next 5 joints at 125 ft, the next 5 joints at 175 ft, and 5 joints at 200 ft. Such an installation would provide field data on which to verify designs of shrinkage-compensating airport pavement overlays with substantially fewer transverse joints.

2. To more accurately establish equivalent steel percentages, it is recommended that an experimental study be conducted to compare expansion of expansive concretes with known steel percentages and those with various steel fiber contents using the same aggregate and mixes and specimen sizes.

ACKNOWLEDGMENTS

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REFERENCES

1. Federal Aviation Administration. Report No. FAA-RD-74-31: Steel Fibrous Concrete for Airport Pavement Applications, by F. Parker, Jr., Nov 1974.

2. Federal Aviation Administration. Report No. FAA-RD-79-11: Shrinkage-Compensating Cement for Airport Pavement, Phase 2, by John R. Keeton, Sep 1979. (Civil Engineering Laboratory Technical Note N-1561)

3. American Society for Testing and Materials. ASTM C806-75: Standard Test Method for Restrained Expansion of Expansive Cement Mortar, Annual Book of ASTM Standards, Part 13, 1979, pp 444-447.

4. American Concrete Institute. Manual of Concrete Practice, Part 3, 544-8, Table 3-2, 1978.

5. Civil Engineering Laboratory. Technical Note N-1504: Expansive Cement Concretes for Naval Construction, by John R. Keeton, Port Hueneme, Calif., Nov 1977.

ASTM STANDARDS CITED

1. ASTM C33-78, "Standard Specification for Concrete Aggregates."

2. ASTM C618-78, "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete."

3. ASTM C231-78, "Air Content of Freshly Mixed Concrete by the Pressure Method."

4. ASTM C39-72, "Test for Compressive Strength of Cylindrical Concrete Specimens."

5. ASTM C78-75, "Test for Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading)."

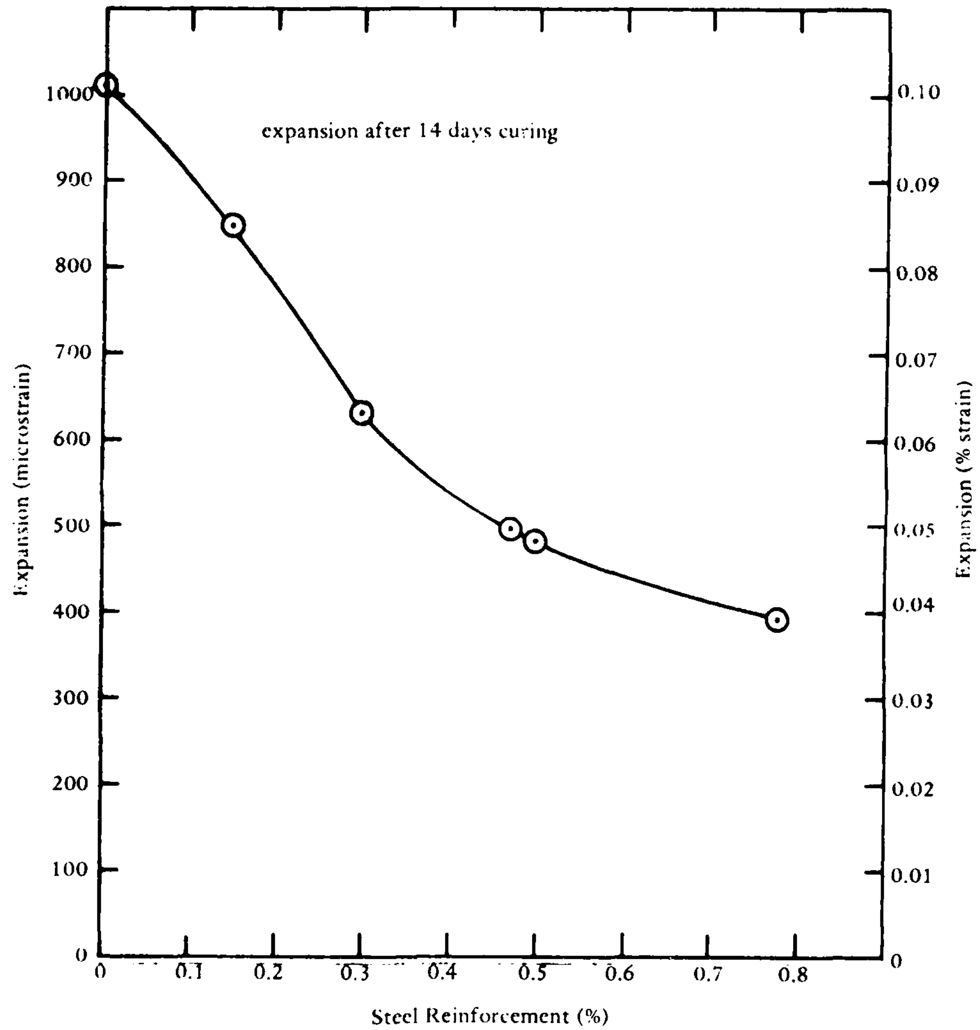

Figure 1. Expansion strains of 1-in.-thick prisms of expansive concrete made with 7.5 bags of shrinkage-compensating cement per cu yd.

TABLE 1. RESEARCH PROGRAM

Mix Designation[a]	Fibers Volume (%)	Prism Thickness (in.)	Number of Prisms
7.9 ECF	1.0	4	4
	1.0	6	4
	1.0	8	4
	1.5	4	4
	1.5	6	6
	1.5	8	4
	2.0	4	4
	2.0	6	4
	2.0	8	4
9.3 ECF[b]	1.0	4	1
	1.0	6	1
	1.0	8	1
	1.5	4	4
	1.5	6	6
	1.5	8	4
	2.0	4	1
	2.0	6	1
	2.0	8	1
10.7 ECF[b]	1.0	4	1
	1.0	6	1
	1.0	8	1
	1.5	4	4
	1.5	6	5
	1.5	8	4
	2.0	4	1
	2.0	6	1
	2.0	8	1

[a] 7.9 refers to 7.9 bags per cu yd (743 lb); 9.3 to 9.3 bags per cu yd (874 lb); 10.7 to 10.7 bags per cu yd (1,006 lb); ECF means expansive concrete with fibers.

[b] At 1.0% and 2.0% fibers, 9.3 ECF and 10.7 ECF prisms were for expansion only; no shrinkage readings were made.

TABLE 2. CONCRETE MIXES

Mix Designation	Fibers Volume (%)	Constituent (cu yd weights)							
		Sand	Gravel	Cement	Fly Ash	Fibers	Water	AEA[a]	Retarder[b]
7.9 ECF	1.0	1,302	1,202	517	222	131	370	216	872
	1.5	1,291	1,191	517	222	194	370	216	872
	2.0	1,281	1,181	517	222	262	370	262	872
9.3 ECF	1.0	1,345	1,102	611	262	131	436	201	1,031
	1.5	1,335	1,092	611	262	194	436	216	1,031
	2.0	1,307	1,082	611	262	262	436	262	1,031
10.7 ECF	1.0	1,271	921	705	302	131	504	262	1,188
	1.5	1,259	912	705	302	194	504	216	1,188
	2.0	1,247	903	705	302	262	504	262	1,188

[a]Air entraining agent in milliliters.

[b]Set retarder in milliliters.

TABLE 3. STRENGTH PROPERTIES OF FIBROUS CONCRETES

Mix Designation	Curing Time	Flexural Strength (psi)			Compressive Strength (psi)			Young's Modulus (psi x 10^6)		
		1.0% Fibers	1.5% Fibers	2.0% Fibers	1.0% Fibers	1.5% Fibers	2.0% Fibers	1.0% Fibers	1.5% Fibers	2.0% Fibers
A. Made With Portland Cement (PCF)										
7.9	28 days	920	1,140	1,050	5,170	6,220	6,940	3.03	3.70	4.30
	3 months	1,100	1,320	1,120	5,810	7,970	8,040	4.05	3.03	2.86
	6 months	1,160	1,390	1,340	6,630	8,630	9,410	4.03	4.13	4.38
9.3	28 days	1,110	1,140	940	6,820	7,180	7,275	3.19	3.92	3.22
	3 months	1,010	1,240	1,120	8,250	8,200	9,490	3.39	3.58	3.80
	6 months	1,260	1,280	1,360	9,000	9,270	9,960	3.95	4.38	4.46
10.7	28 days	1,100	1,180	1,120	8,250	8,550	7,760	3.88	2.90	3.88
	3 months	1,140	1,270	1,220	9,070	9,350	9,550	4.03	4.38	4.13
	6 months	1,180	1,200	1,300	9,370	10,240	10,980	4.16	5.13	4.38
B. Made With Expansive Cement (ECF)										
7.9	28 days	900	1,080	960	5.720	6.160	7,320	3.32	3.83	4.06
	3 months	1,080	1,180	1,150	7,280	7,780	9,010	3.53	2.94	4.13
	6 months	1,120	1,300	1,180	8,720	9,100	9,710	4.37	4.13	5.04
9.3	28 days	980	980	1,180	7,110	7,570	8,040	3.95	3.35	2.68
	3 months	1,070	1,080	1,220	9,310	9,710	10,070	4.33	3.68	4.39
	6 months	1,160	1,340	1,250	9,470	10,140	10,200	4.22	4.16	4.69
10.7	28 days	980	1,050	1,090	8,190	9,390	8,990	3.34	4.65	4.55
	3 months	1,020	1,200	1,290	--	9,470	10,880	--	4.30	4.38
	6 months	1,200	1,260	1,300	10,820	11,160	11,900	4.78	3.61	4.75

TABLE 4. 28-DAY CONCRETE EXPANSIONS

Prism Thickness (in.)	Depth From Top (in.)	Mix Designation	Expansion (microstrain)		
			1.0% Fibers	1.5% Fibers	2.0% Fibers
4	1	7.9 ECF	518	441	299
		9.3 ECF	581	489	336
		10.7 ECF	650	537	375
	3	7.9 ECF	432	362	258
		9.3 ECF	489	407	290
		10.7 ECF	543	450	325
6	1	7.9 ECF	532	444	300
		9.3 ECF	612	500	345
		10.7 ECF	690	556	386
	3	7.9 ECF	442	371	261
		9.3 ECF	510	419	298
		10.7 ECF	580	467	330
	5	7.9 ECF	382	329	235
		9.3 ECF	440	360	263
		10.7 ECF	500	390	287
8	1	7.9 ECF	546	450	301
		9.3 ECF	640	526	355
		10.7 ECF	738	602	405
	4	7.9 ECF	457	373	257
		9.3 ECF	540	438	298
		10.7 ECF	625	502	338
	7	7.9 ECF	405	340	235
		9.3 ECF	477	395	265
		10.7 ECF	546	450	297

TABLE 5. SHRINKAGE IN 50% RH - 1 INCH FROM TOP

Mix Designation	Fibers Volume (%)	Prism Thickness (in.)	Shrinkage (microstrain) After--						
			50 Days	100 Days	150 Days	200 Days	250 Days	300 Days	365 Days
7.9 ECF	1.0	4	300	420	455	470	475	480	485
		6	275	410	445	460	470	475	475
		8	255	390	425	445	450	455	460
	1.5	4	340	425	450	465	470	475	480
		6	315	405	430	440	445	450	455
		8	300	385	405	420	405	430	430
	2.0	4	275	395	420	430	435	435	440
		6	255	375	395	410	415	415	420
		8	240	355	375	385	395	395	400
9.3 ECF	1.5	4	310	410	435	450	455	455	460
		6	300	395	425	435	440	445	445
		8	280	380	405	415	420	425	425
10.7 ECF	1.5	4	330	405	425	435	440	445	450
		6	315	395	415	425	430	435	435
		8	295	385	405	415	420	420	425

TABLE 6. SHRINKAGE IN 50% RH - 3 INCHES FROM TOP

Mix Designation	Fibers Volume (%)	Prism Thickness (in.)	Shrinkage (microstrain) After--						
			50 Days	100 Days	150 Days	200 Days	250 Days	300 Days	365 Days
7.9 ECF	1.0	4	215	360	400	415	425	430	435
		6	175	320	370	390	400	405	410
	1.5	4	220	355	395	410	420	425	435
		6	200	335	375	390	400	405	415
	2.0	4	225	360	385	390	395	400	400
		6	195	335	365	375	375	380	380
9.3 ECF	1.5	4	170	295	330	350	355	360	365
		6	155	275	310	325	335	340	345
10.7 ECF	1.5	4	200	370	400	410	420	420	425
		6	185	345	380	385	400	405	405

TABLE 7. SHRINKAGE IN 50% RH - 4 INCHES FROM TOP

Mix Designation	Fibers Volume (%)	Prism Thickness (in.)	Shrinkage (microstrain) After--						
			50 Days	100 Days	150 Days	200 Days	250 Days	300 Days	365 Days
7.9 ECF	1.0	8	145	255	285	300	305	305	310
	1.5	8	130	250	290	310	320	325	330
	2.0	8	155	250	265	275	275	280	280
9.3 ECF	1.5	8	125	240	280	300	310	315	320
10.7 ECF	1.5	8	160	280	315	335	340	345	350

TABLE 8. RESIDUAL EXPANSION AFTER 1 YEAR IN 50% RH - 1 INCH FROM TOP

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Expansion (microstrain)	Shrinkage (microstrain)	Residual (microstrain)
4	7.9 ECF	1.0	518[a]	-485	33
		1.5	441	-480	-39
		2.0	299	-440	-141
	9.3 ECF	1.0	581	-465[a]	116
		1.5	489	-460	29
		2.0	336	-422[a]	-86
	10.7 ECF	1.0	650	-455a	195
		1.5	537	-450	87
		2.0	375	-412[a]	-37
6	7.9 ECF	1.0	532	-475	57
		1.5	444	-455	-11
		2.0	300	-420	-120
	9.3 ECF	1.0	612	-465[a]	147
		1.5	500	-445	55
		2.0	345	-411[a]	-66
	10.7 ECF	1.0	690	-454[a]	236
		1.5	556	-435	121
		2.0	386	-402[a]	-16
8	7.9 ECF	1.0	546	-460	86
		1.5	450	-430	20
		2.0	301	-400	-99
	9.3 ECF	1.0	640	-455[a]	185
		1.5	526	-425	101
		2.0	355	-395[a]	-40
	10.7 ECF	1.0	738	-455[a]	283
		1.5	602	-425	177
		2.0	405	395[a]	10

[a]Estimated shrinkages based on relationships among shrinkages for 7.9 ECF at 1.0, 1.5, and 2.0% fibers (see text).

TABLE 9. RESIDUAL EXPANSION AFTER 1 YEAR IN 50% RH - 3 INCHES FROM TOP

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Expansion (microstrain)	Shrinkage (microstrain)	Residual (microstrain)
4	7.9 ECF	1.0	432	-435	-3
		1.5	362	-435	-73
		2.0	258	-400	-142
	9.3 ECF	1.0	489	-365[a]	124
		1.5	407	-365	42
		2.0	290	-336[a]	-46
	10.7 ECF	1.0	543	-425[a]	118
		1.5	450	-425	25
		2.0	325	-391[a]	-66
6	7.9 ECF	1.0	442	-410	32
		1.5	371	-415	-44
		2.0	261	-380	-119
	9.3 ECF	1.0	510	-341[a]	169
		1.5	419	-345	74
		2.0	298	-316[a]	-18
	10.7 ECF	1.0	580	-400[a]	180
		1.5	467	-405	62
		2.0	330	-371[a]	-41

[a]Estimated shrinkages based on relationships among shrinkages for 7.9 ECF at 1.0, 1.5, and 2.0% fibers (see text).

TABLE 10. RESIDUAL EXPANSION AFTER 1 YEAR IN 50% RH - 4 INCHES FROM TOP

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Expansion (microstrain)	Shrinkage (microstrain)	Residual (microstrain)
8	7.9 ECF	1.0	457[a]	-310	147
		1.5	373	-330	43
		2.0	257	-280	-23
	9.3 ECF	1.0	540	-301[a]	239
		1.5	438	-320	118
		2.0	298	-272[a]	26
	10.7 ECF	1.0	625	-329[a]	296
		1.5	502	-350	152
		2.0	338	-297[a]	41

[a]Estimated shrinkages based on relationships among shrinkages for 7.9 ECF at 1.0, 1.5, and 2.0% fibers (see text).

TABLE 11. ONE YEAR SHRINKAGE AT 20% RH

Mix Designation	Fibers Volume (%)	Prism Thickness (in.)	Shrinkage (microstrain)		
			1 Inch From Top	3 Inches From Top	4 Inches From Top
7.9 ECF	1.0	4	630[a]	566	--
		6	618	533	--
		8	598	--	403
	1.5	4	624	566	--
		6	592	540	--
		8	559	--	429
	2.0	4	572	520	--
		6	546	494	--
		8	520	--	364
9.3 ECF	1.0	4	604[a]	474	--
		6	604	443	--
		8	592	--	391
	1.5	4	598	474	--
		6	592	448	--
		8	552	--	416
	2.0	4	549	437	--
		6	534	411	--
		8	514	--	354
10.7 ECF	1.0	4	592[a]	552	--
		6	590	520	--
		8	592	--	428
	1.5	4	585	552	--
		6	566	526	--
		8	552	--	455
	2.0	4	536	508	--
		6	523	482	--
		8	514	--	386

[a]Estimated from shrinkages at 50% RH as follows: shrinkage at 20% RH = shrinkage at 50% RH x 1.3.

TABLE 12. RESIDUAL EXPANSION AFTER 1 YEAR AT 20% RH - 1 INCH FROM TOP

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Expansion (microstrain)	Shrinkage (microstrain)	Residual (microstrain)
4	7.9 ECF	1.0	518	-630	-112
		1.5	441	-624	-183
		2.0	299	-572	-273
	9.3 ECF	1.0	581	-604	-23
		1.5	489	-598	-109
		2.0	336	-549	-213
	10.7 ECF	1.0	650	-592	58
		1.5	537	-585	-48
		2.0	375	-536	-161
6	7.9 ECF	1.0	532	-618	-86
		1.5	444	-592	-148
		2.0	300	-546	-246
	9.3 ECF	1.0	612	-604	8
		1.5	500	-592	-92
		2.0	345	-534	-189
	10.7 ECF	1.0	690	-590	100
		1.5	556	-566	-10
		2.0	386	-523	-137
8	7.9 ECF	1.0	546	-598	-42
		1.5	450	-559	-109
		2.0	301	-520	-219
	9.3 ECF	1.0	640	-592	48
		1.5	526	-552	-26
		2.0	355	-514	-159
	10.7 ECF	1.0	738	-592	146
		1.5	602	-552	50
		2.0	405	-514	-109

TABLE 13. RESIDUAL EXPANSION AFTER 1 YEAR AT 20% RH - 3 INCHES FROM TOP

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Expansion (microstrain)	Shrinkage (microstrain)	Residual (microstrain)
4	7.9 ECF	1.0	432	-566	-134
		1.5	362	-566	-204
		2.0	258	-520	-262
	9.3 ECF	1.0	489	-474	15
		1.5	407	-474	-67
		2.0	290	-437	-147
	10.7 ECF	1.0	543	-552	-9
		1.5	450	-552	-102
		2.0	325	-508	-183
6	7.9 ECF	1.0	442	-533	-91
		1.5	371	-540	-169
		2.0	261	-494	-233
	9.3 ECF	1.0	510	-443	67
		1.5	419	-448	-29
		2.0	298	-411	-113
	10.7 ECF	1.0	580	-520	60
		1.5	467	-526	-59
		2.0	330	-482	-152

TABLE 14. RESIDUAL EXPANSION AFTER 1 YEAR AT 20% RH - 4 INCHES FROM TOP

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Expansion (microstrain)	Shrinkage (microstrain)	Residual (microstrain)
8	7.9 ECF	1.0	457	-403	54
		1.5	373	-429	-56
		2.0	257	-364	-107
	9.3 ECF	1.0	540	-391	149
		1.5	438	-416	22
		2.0	298	-354	-56
	10.7 ECF	1.0	625	-428	197
		1.5	502	-455	47
		2.0	338	-386	-48

TABLE 15. RESIDUAL COMPRESSIVE STRAINS AFTER 1 YEAR AT 50% RH

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Compressive Strain (microstrain)		
			1 Inch From Top	3 Inches From Top	4 Inches From Top
4	9.3 ECF	1.0	116	124	--
		1.5	29	42	--
	10.7 ECF	1.0	195	118	--
		1.5	87	25	--
6	7.9 ECF	1.0	57	32	--
	9.3 ECF	1.0	147	169	--
		1.5	55	74	--
	10.7 ECF	1.0	236	180	--
		1.5	121	62	--
8	7.9 ECF	1.0	86	--	147
		1.5	20	--	43
	9.3 ECF	1.0	185	--	239
		1.5	101	--	118
	10.7 ECF	1.0	283	--	296
		1.5	177	--	152
		2.0	10	--	41

TABLE 16. RESIDUAL COMPRESSIVE STRAINS AFTER 1 YEAR AT 20% RH

Prism Thickness (in.)	Mix Designation	Fibers Volume (%)	Compressive Strain (microstrain)		
			1 Inch From Top	3 Inches From Top	4 Inches From Top
6	9.3 ECF	1.0	8	67	--
	10.7 ECF	1.0	100	60	--
8	9.3 ECF	1.0	48	--	149
	10.7 ECF	1.0	146	--	197
		1.5	50	--	47

TABLE 17. STEEL PERCENTAGES FOR FIBER VOLUMES OBTAINED FROM REFERENCE 5

Prism Thickness (in.)	Fibers Volume (%)	Steel Percentages
4	1.0	0.33
	1.5	0.47
	2.0	>0.80
6	1.0	0.33
	1.5	0.51
	2.0	>0.80
8	1.0	0.30
	1.5	0.42
	2.0	>0.80

TABLE 18. RESIDUAL CONCRETE COMPRESSIVE STRESSES FOR 10.7 ECF MIX AFTER ONE YEAR AT 50% RH

Prism Thickness (in.)	Fibers Volume (%)	Compressive Stress (psi)
4	1.0	14
	1.5	7
6	1.0	19
	1.5	13
8	1.0	24
	1.5	19

TABLE 19. RESIDUAL CONCRETE COMPRESSIVE STRESSES FOR 10.7 ECF MIX AFTER ONE YEAR AT 20% RH

Prism Thickness (in.)	Fibers Volume (%)	Compressive Stress (psi)
6	1.0	7
	1.5	N/A
8	1.0	14
	1.5	6

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